Design and quality evaluation of micro-optical freeform beam shapers

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Summary

A method to generate thin micro-optical freeform (MOF) beam shapers by wrapping a much thicker freeform surface is provided. The influence of parameters such as the clipping factor *q*, the design wavelength and the spectrum of the light source into the quality of the output distributions has been studied.

Introduction

Progress in micro-fabrication has enabled not only diffractive optical elements (DOE) but also complex freeform surfaces [1]. Transmissive optical elements can be mainly classified into refractive and diffractive. Ray-tracing techniques are sufficient to explain light propagation through and beyond refractive elements. On the other hand, since interferences are the basis of the diffractive domain, the wave behavior of light must be contemplated in their design. When comparing the topography of elements from each domain, the refractive one is characterized by surfaces with macroscopic continuous features which are mostly insensitive to the wavelength of light. Conversely, DOEs wavelength dependence is prominent, since they are thin elements with microscopic features that modulate incident light by means of diffraction.

A miniaturization and/or flattening of freeform beam-shaping structures is sought, since it will ensure compactness and hence better system integration, without impairing their optical performance. This work presents a top-down approach to design hybrid beam-shaping structures, micro-optical freeform (MOF) elements, and moreover studies the limits between the two domains. The limitations of the fabrication method are also considered in this design strategy.

Design method

MOF element design starts by the generation of a freeform beam-shaping surface [2] followed by lateral and vertical scaling, in order to downsize the original surface and/or its projection distance. A further reduction in thickness of the element can be achieved by wrapping or clipping its surface profile, while keeping the tendue constant. This procedure is described by the following equations:

$$h_c(\mathbf{x}) = h(\mathbf{x})\mathrm{mod}H_c \tag{1}$$

$$H_c = q\lambda_\mathrm{D}/\Delta n(\lambda_\mathrm{D}) \tag{2}$$

where $q \subset \mathbb{R}_{>0}$ is the clipping factor, λ_D is the design wavelength, and $\Delta n(\lambda)$ is the refractive index difference. For the special case of q=1, the wrapping or clipping height H_c corresponds to a 2π-phase shift of the output light field. The schematic on Fig. 1 shows the typical arrangement for a MOF beam shaper. The clipping method can significantly reduce the thickness of the MOF beam shaper at the expense of introducing multiple folds in the otherwise highly continuous surface. Therefore, it exists a tradeoff between output image quality and vertical compactness of the beam shaper.

Simulation results

Free-space light propagation beyond the MOF elements has been simulated by means of the angular spectrum of planar waves method in Matlab. The structures have been approximated as thin phase elements. In order to both respect sampling constraints and consider fabrication inaccuracies of sharp edges into the simulations, the clipped height profile has been convoluted with a Gaussian filter. Signal-to-noise ratio (SNR) has been used as merit function to evaluate the quality of the output intensity distributions.

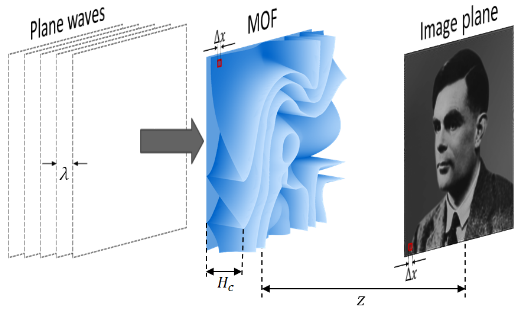

Fig 1: Schematic showing the setup of a MOF beam shaper as well as some relevant parameters. Dimensions have been scaled for illustrative reasons.

The quality evaluation shown at Fig. 2 reveals that, for single wavelength illumination, only at integer clipping factor values the image signal is much above the noise level. Otherwise light interferes destructively to impair the target intensity distribution. In the case of broad spectrum illumination (5 wavelengths) it is assumed that partially coherent light is a superposition of irradiance from uncorrelated coherent waves. Contrary to the monochromatic illumination results, the SNR curves do not drop to 1. This can be explained by the fact that the coherence length of the colorful source is much shorter than that of the monochromatic plane wave, and than the clipping height H_c of the MOF element. Moreover, the SNR curves do not increase linearly as they did in the case of monochromatic illumination (at integer clipping factors). Indeed, the oscillation amplitude decreases with q and the expected trend is that SNR reaches a certain saturation value.

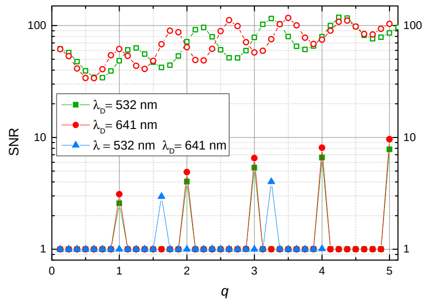

Fig 2: SNR as function of clipping factor for different design wavelengths and monochromatic (solid symbols and lines) and five wavelength (empty symbols and dashed lines) illumination of the MOF element.

Conclusions

A design method of compact MOF beam shapers has been proposed by wrapping the original freeform surface profile. Monochromatic and multiple wavelength planar wave illumination has been propagated through the structures and the fidelity of the results with respect to the reference distributions has been evaluated. Single wavelength illumination reveals that at non-integer clipping factors the quality of the resulting intensity distribution is extremely poor, due to the large coherence length of the light source. In the conditions of broadband illumination, a shorter coherence length of the source than the clipping height H_c allows better quality along the whole range of clipping factors, not only at specific values. Quality increases with q in an oscillatory way but the amplitude of these oscillations tends to decrease.

References

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